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GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

Hard copy (HC) \$ 3.00

Microfiche (MF) .65

ff 653 July 65

FACILITY FORM 802	N 67-27647	
	(ACCESSION NUMBER)	(THRU)
	1037RS22-25	1
	(PAGES)	(CODE)
	29A CR 84492 29B	30
	(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Report No. P-19

SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS:
JUPITER AS AN OBJECT OF BIOLOGICAL INTEREST

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Report No. SP-19 END


3 SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS: 2#
1 JUPITER AS AN OBJECT OF BIOLOGICAL INTEREST

by
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NASA Headquarters
Washington, D. C.

Contract No. NASr-65(06)- 29ACV

25
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9 May 1967 10

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FOREWORD

The principal contributor to Section 3 of this report was A. Weinstock (Life Sciences Division, IITRI). Section 2 was prepared in consultation with T. Owen (Astro Sciences Center), while Section 4 and the general organization of the report were developed by D. L. Roberts and C. A. Stone (Astro Sciences Center).

ABSTRACT

The report discusses the Jovian environment; some of the biological systems that conceivably could evolve under such conditions; a brief discussion of current ideas about the origin of terrestrial life; an assessment of the importance of Jupiter from a biological point of view; and, the effect of this information on the planning of conventional observations and spacecraft missions to the planet for purposes of scientific exploration.

It is concluded that presently available evidence justifies a biological exploration of Jupiter with early emphasis on the atmosphere below the clouds.

SUMMARY

The exobiologists' expectations for finding extraterrestrial life in the solar system traditionally have been focused on the inner planets, with particular attention directed at Mars. Formerly, it was generally believed that the distant outer planets, such as Jupiter, would be too cold, and that their atmospheres might be composed of substances that were inimical to the survival of life, as it is known on the Earth.

This report indicates that the former pessimism regarding the possible existence of life on Jupiter may no longer be justified. Although information about the Jovian atmosphere is at present limited, conditions may prevail on the planet which are compatible with the existence of a primitive biological environment. This assumption is supported by some evidence, as well as recent theories.

The report discusses the Jovian environment; some of the biological systems that conceivably could evolve under such conditions; a brief discussion of current ideas about the origin of terrestrial life; an assessment of the importance of Jupiter from a biological point of view; and, the effect of this information on the planning of conventional observations

and spacecraft missions to the planet for purposes of scientific exploration.

As ideas about the origin of life on the Earth have become more sophisticated and supported by experimental investigations, it has become reasonably apparent that the conditions which existed on the Earth at the time that terrestrial biogenesis occurred were not unlike those that are assumed to characterize the lower strata of Jupiter's atmosphere. Also, an increasing amount of knowledge obtained about the Jovian environment during recent years suggests the possibility that the planet's atmosphere is highly reducing and that relatively temperate regions containing liquid water as clouds, or even seas, may occur at levels below those which are visible by direct observation. The increased temperatures in the lower strata may be produced in part by the "greenhouse" effect of solar heat trapped in the planet's atmosphere.

Jupiter's atmosphere appears to have the same relative composition as that suggested by the solar abundance of the elements. The Jovian atmosphere is known to contain methane, ammonia, and hydrogen, while the presence of helium is inferred by indirect analysis. The presence of free oxygen and nitrogen is not expected to be found, however, since in a reducing hydrogen-rich atmosphere, these gases would have combined with hydrogen to form water and ammonia, respectively. Oxygen-containing compounds such as carbon dioxide and carbon monoxide, would similarly be reduced to water and methane, with the water

frozen out at the temperatures of the upper atmosphere.

In successful laboratory experiments, simulated Jovian-type atmospheres have been subjected to ultraviolet radiation, electric discharges, ionizing radiation, and heat, which resulted in the production of such compounds as adenine and hydrocyanic acid, as well as amino acids and other complex organic substances. Such compounds generally are considered to be necessary precursors to the simple forms of life, since they form the building blocks for the nucleic acids and proteins which are vital elements of living organisms.

In addition to this evidence for the possible existence of biological precursors on Jupiter, it should be noted that certain types of primitive organisms which presently exist on the Earth also could possibly survive in the Jovian environment. These organisms, as for example, anaerobic methane bacteria (which apparently are able to take in hydrogen and release methane), might have evolved on the Earth under conditions such as those which now exist on Jupiter, and managed to survive to our era in highly specific micro-environments. Also, consideration must be given to the possibility that life forms in the process of development on Jupiter may have evolved in a manner completely different from that of terrestrial life. An example of this would be the use of liquid ammonia instead of water as a biological substrate.

The origin of terrestrial life is thought to have passed through three distinct chemical phases: inorganic to organic to

biological. The generation of life on the Earth's surface must have been preceded by a preliminary development of those organic substances of which organisms are constituted. If positive evidence was found on Jupiter, of the synthesis of organic matter in the presence of a primitive reducing atmosphere, it would provide support for present concepts of the evolution of organized matter. Also, negative findings would be meaningful since they would necessitate reorientation of present thinking as well as a re-evaluation of laboratory experiments employing simulated reducing atmospheres.

The scientific exploration of Jupiter should include additional ground-based or near-Earth observations to obtain more information about the presence of organic molecules, water, and temperature regimes at various atmospheric levels. Such data could later be refined by means of spacecraft flyby and orbiter missions. However, since the most revealing and interesting part of the planet from the biological standpoint is the region below the clouds, atmospheric probes, survivable and non-survivable, may be required to explore that region. Therefore, spacecraft missions which lead to the deployment of such probes should be given the highest priority for the biological exploration of Jupiter.

The report concludes that presently available evidence regarding the Jovian environment, together with current ideas about the mode for the development of life on the Earth, justify plans for a biological exploration of Jupiter.

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SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS:
JUPITER AS AN OBJECT OF BIOLOGICAL INTEREST

1. INTRODUCTION

As part of a continuing effort in assisting NASA's advanced planning for space missions, ASC/IITRI has outlined the important scientific objectives for the exploration of the planets. These objectives have been primarily in the realm of the physical sciences. Since one of the stated goals of the space program is the investigation of the origin and evolution of life, it is apparent that some consideration of the possible significance of the planets for biological studies must also be undertaken. One report of this kind has already been completed: "Mission Requirements for Exobiological Measurements on Venus," ASC/IITRI Report No. P-16.

The present report discusses the environment on Jupiter, some of the biological systems that conceivably could evolve under such conditions, and the effect of this information on mission planning. While it must be recognized that definitive data characterizing the Jovian atmosphere are presently limited, the assumption is made that conditions may prevail on Jupiter

which are compatible with the existence of a primitive biological preserve. It is felt that the evidence presented in the following pages fully justifies this assumption.

In considering the planets from a biological viewpoint, it has been customary to ignore Jupiter, or to assign it a very low rating. The low temperatures and highly reducing atmosphere that had been found to characterize this planet appeared to preclude the existence of life as we know it from experience with terrestrial biology. In the last few years, however, observations of Jupiter have indicated relatively high temperatures in and below the clouds, while the possibility of the presence of some water in these lower strata has become more likely. In addition, a growing number of laboratory experiments and theoretical arguments have emphasized that the conditions required for the origin of life on our own planet were undoubtedly different from the conditions that exist today. In fact, it appears that these original conditions were not unlike those presently existing on the planet Jupiter. As a result, it is apparent that the new model for the atmosphere of Jupiter which is emerging could have profound biological implications.

The presence of a primitive reducing atmosphere on Jupiter provides a unique opportunity to go "back in time," so to speak, and endeavor to relate a possible exobiology on Jupiter to the conditions existing during biogenesis on the Earth. Positive evidence of the synthesis of organic matter on Jupiter would be of great significance in that it would

provide support for present concepts of the evolution of organized matter. On the other hand, negative findings would also be very meaningful since they would necessitate a reorientation of present thinking as well as a re-evaluation of laboratory experiments employing simulated reducing atmospheres. It is possible, of course, that more than one pathway toward the development of life exists. Abelson (1966) has presented some preliminary arguments for a model in which life develops in an atmosphere that does not contain methane and ammonia. It may be that the direct investigation of a totally alien biology represents the only means available for deciding which of the various possibilities actually lead to living entities.

A brief description of our present knowledge of those aspects of the Jovian environment relevant to a biological investigation of the planet is presented in Section 2. A brief discussion of current ideas about the origin of terrestrial life is presented in Section 3, and this background material is then used to assess the importance of Jupiter from a biological point of view. Section 4 contains a discussion of the biological desiderata, the additional information about the planet that must be obtained from conventional observations and from space missions to test the conclusions reached in this analysis.

2. THE JOVIAN ENVIRONMENT

The atmospheres of the terrestrial planets are thought to be secondary, having been produced by outgassing after the

primitive atmospheres were dissipated. Jupiter, however, appears to have retained a large fraction of its primitive atmosphere, with approximately the same relative composition as that suggested by the solar abundance of the elements. Methane, ammonia, and hydrogen are known to exist in the atmosphere of Jupiter, while the presence of a substantial amount of helium is inferred from indirect analysis.

Models for the Jovian atmosphere contain about 80 per cent hydrogen by mass; a value consistent with the available evidence for the solar hydrogen abundance. At the pressures (0.5 to 1.0 atm) and temperatures (125 to 175°K) believed to exist near Jupiter's visible (cloud) surface, methane is found only in the gaseous phase. The temperature appears to be low enough for ammonia to be present in both the solid and the gaseous phases, with changes of phase occurring constantly at varying height and temperature. These changes of phase must play an important role in the thermodynamics of Jupiter's atmosphere, as do changes of phase of water in the Earth's atmosphere. The presence of free oxygen or nitrogen is not expected since in a reducing hydrogen-rich atmosphere these gases would have combined with hydrogen to form water and ammonia, respectively. Oxygen containing compounds, e.g., carbon dioxide and carbon monoxide, would similarly be reduced to water and methane with the water being frozen out at the temperatures of the upper atmosphere.

Photochemical reactions occurring in an atmosphere of Jupiter's composition presage the possible presence of additional constituents such as ethane, hydrogen cyanide, acetylene, etc. It has not, however, been possible as yet to verify the presence of any of these compounds, primarily because the UV region of the spectrum is presently inaccessible to ground-based observations and the instrumental IR is only beginning to be explored with adequate resolution. Witting, Cann, and Owen (1965) note that there are two principal arguments for postulating the presence of small quantities of polyatomic molecules other than those observed directly. One is purely theoretical, based on likely photochemical reactions which should occur in a Jovian-type atmosphere. The second is the evidence presented by the colors observed in the visible cloud layers. The agents responsible for these colors are presently unidentified, but Wildt (1939) has suggested solutions of sodium in ammonia as an explanation, particularly since sodium has been found in the Earth's upper atmosphere. An additional source of coloration is needed, however, since sodium-ammonia solutions only produce blues and grays. Urey (1959) has suggested complex organic molecules as this source. Sagan, Lippincott, Dayhoff and Eck (1967) have shown from chemical equilibrium calculations that such molecules can be produced in the Jovian atmosphere at high temperatures, e.g., by lightning discharges or by solar UV irradiation. Greenspan and Owen (1967) have suggested that a presently unidentified absorption near 2600 Å

in the spectrum of Jupiter is probably caused by one or more organic compounds of considerable complexity. If a positive identification of this absorption could be made, one might then have direct evidence for the presence of at least one organic complex. Alternatively, Papazian (1959) postulated that the color induced in certain condensates by charged particle bombardment could explain the Jupiter colors. The planet's atmosphere would be readily penetrated by 100-mev particles, which are fairly abundant in interplanetary space.

The rapidly changing details of Jupiter's cloud formations indicate that the atmosphere is in a considerable state of turbulence with intermingling of gases at various levels continually taking place. Little is known, however, about Jupiter's atmosphere below the cloud level although Gallet (1963) has undertaken a theoretical analysis of this region. With allowance for the heat released in the condensation of NH_3 at the temperature and density of the visible cloud top, he deduced that there should be a relatively slow increase in temperature with decreasing altitude below the clouds. Gallet further suggested that the observed cloud layer may be 50 km of ammonia, below which there is another deck of clouds composed of water. Measurements made by Owen (1965) indicate that there is a 200 to 250°K temperature zone beneath the clouds in which it is very likely (from solar abundance arguments) that water is present. Sagan (1961) postulates that if Jupiter has a surface which is opaque to visible light, this surface will be

heated by light penetrating through the cloud layer and will emit in the infrared. Because of the absorptive properties of the Jovian atmosphere, infrared radiation will be unable to escape to space and a very efficient greenhouse effect could be established. Under these conditions, the temperature of the Jovian atmosphere will increase with depth below the visible cloud layer, i.e., the atmospheric "greenhouse" provides a mechanism for producing the observed high temperatures. In addition, Low (1966) has detected a surplus of radiation from Jupiter at 10μ and 20μ which he interprets as intrinsic thermal radiation from the planet in excess of the amount absorbed from the Sun. In other words, it appears that the planet itself is a source of thermal energy, probably as a result of a slow, continual gravitational contraction. This again is evidence for relatively high temperatures below the clouds.

The significance of these results for the present discussion is obvious; at temperatures above 273°K we may anticipate the existence of liquid water, either as clouds in the atmosphere, or as seas if there exists a surface of sufficient integrity to support them. A logical deduction based on all this evidence is that organic matter could be produced in this environment in a manner analogous to the processes which supposedly led to the synthesis of organic molecules in the early history of the Earth.

3. EXOBIOLOGY OF JUPITER

3.1 Initial Stages in the Development of Terrestrial Life

To provide some basis for assessing the biological importance of the environmental characteristics just discussed, one can consider the origin and evolution of life on Earth. It is important to keep the distinction between these two words (origin and evolution) in mind. After life originates, subsequent evolution may alter the environment drastically, to the point where life could no longer originate under existing conditions. The origin of terrestrial life was a gradual process operating over an extremely long span of time, perhaps millions of years. The process of origin is thought to have passed through three distinct chemical phases; from inorganic to organic chemistry and hence from organic to biological chemistry (Fig. 1). Inevitably the generation of life on the Earth's surface must have been preceded by a preliminary development of those organic substances of which organisms are constituted.

Most of the available evidence seems to support the assumption that carbon, at least in part, first appeared on the Earth's surface in the reduced form, particularly as hydrocarbons, with nitrogen likewise in a reduced state in the form of ammonia. This is suggestive of the present composition of the Jupiter atmosphere.

Bernal (1951) sums up the initial sequences of the origin of life as follows: First, simple organic molecules such as hydrocarbons were created in the primitive reducing

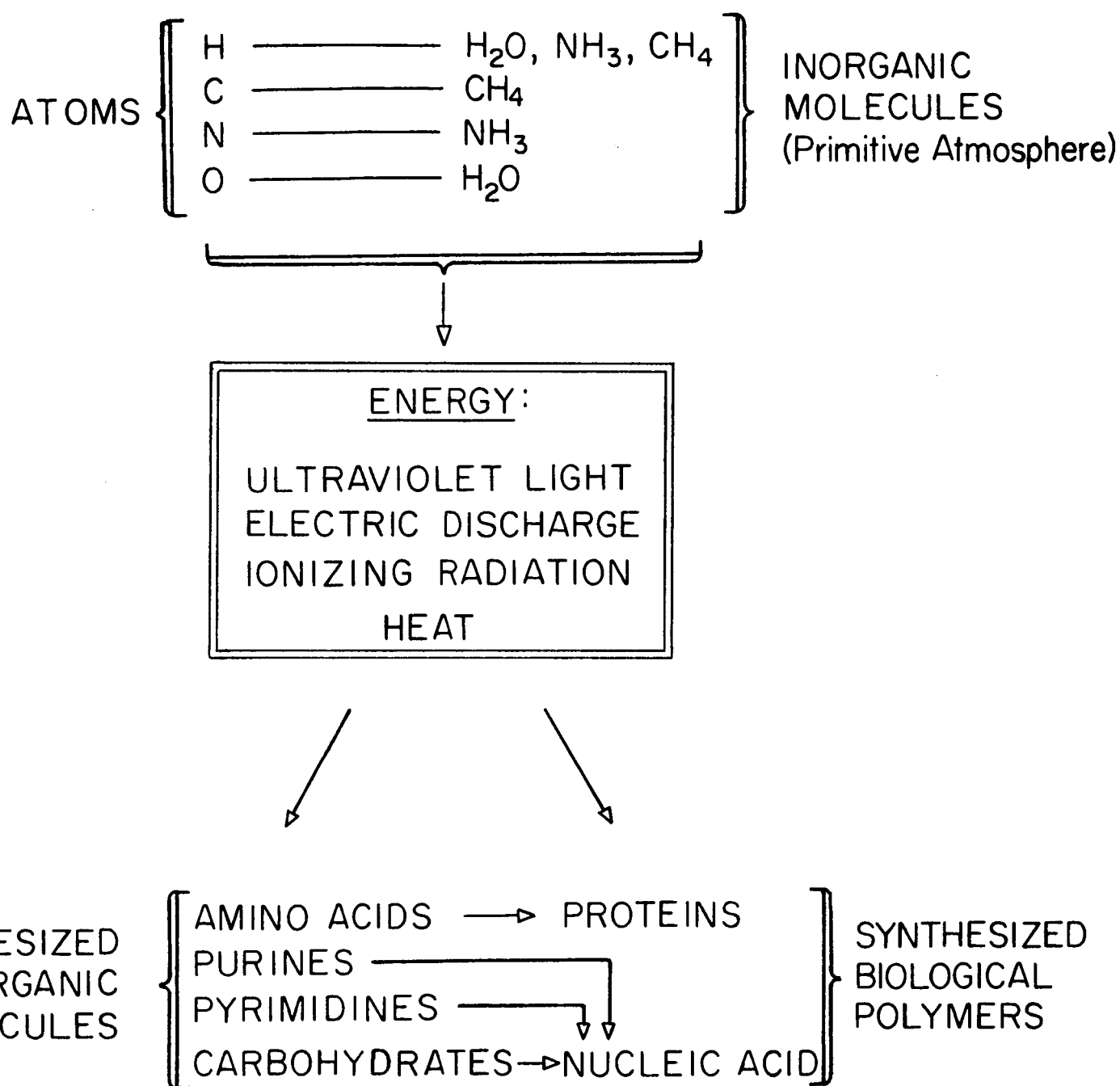


FIGURE 1. POSSIBLE SYNTHESIS OF ORGANIC COMPOUNDS ON THE PRIMITIVE EARTH (ADAPTED FROM YOUNG AND PONNAMPERUMA, 1964)

atmosphere. Then over a long period of time, more complex molecules and polymers were produced (Fig. 1). These became concentrated and organization occurred. Natural selection favored some of the resulting systems and from them the first living things arose, namely single cell entities (Fig. 2). If oxygen concentrations sufficient to permit respiration became available there would be a corresponding demand for complex biological functions leading to multi-celled organisms with advanced mechanisms of energy reception, control, and utilization. At this stage, the processes governing the evolution of life would begin operating in earnest. Wald (1964) states that the present organization of cellular metabolism together with what can be surmised to have been the course of its evolution, provides internal evidence that organisms went through much of their early development in the absence of oxygen. Otherwise, it would be difficult to comprehend the ingenuity they have displayed in developing anaerobic pathways of metabolism. Actually, the whole basic structure of cellular metabolism is anaerobic and virtually all types of cells that are deprived of oxygen can survive for extended periods on fermentation.

This brief sketch should indicate that the Jovian environment may indeed be promising from a biological viewpoint. In fact, one can envisage several strata of complex chemicals which might build into a biosphere on Jupiter. Highly complex organic molecules might be produced from solar radiation and

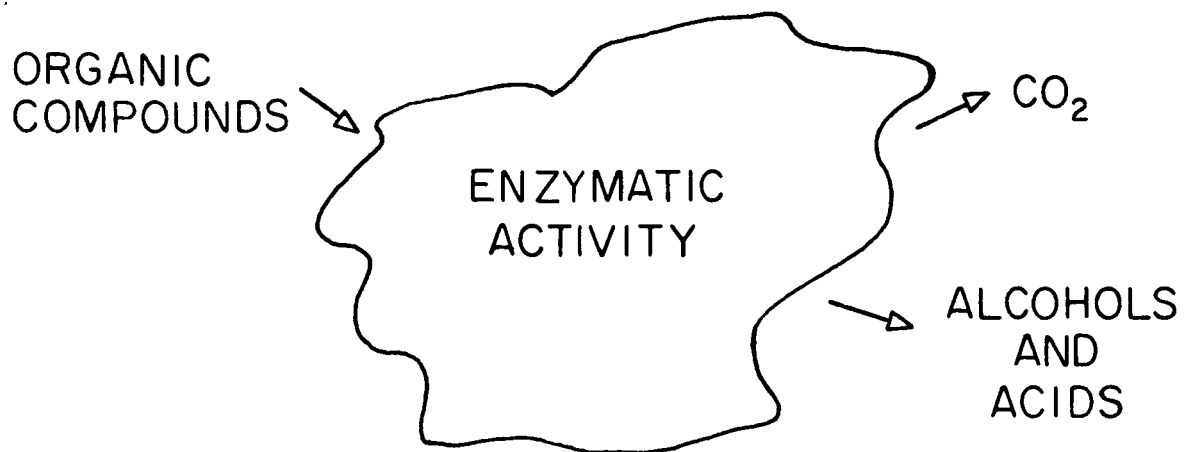
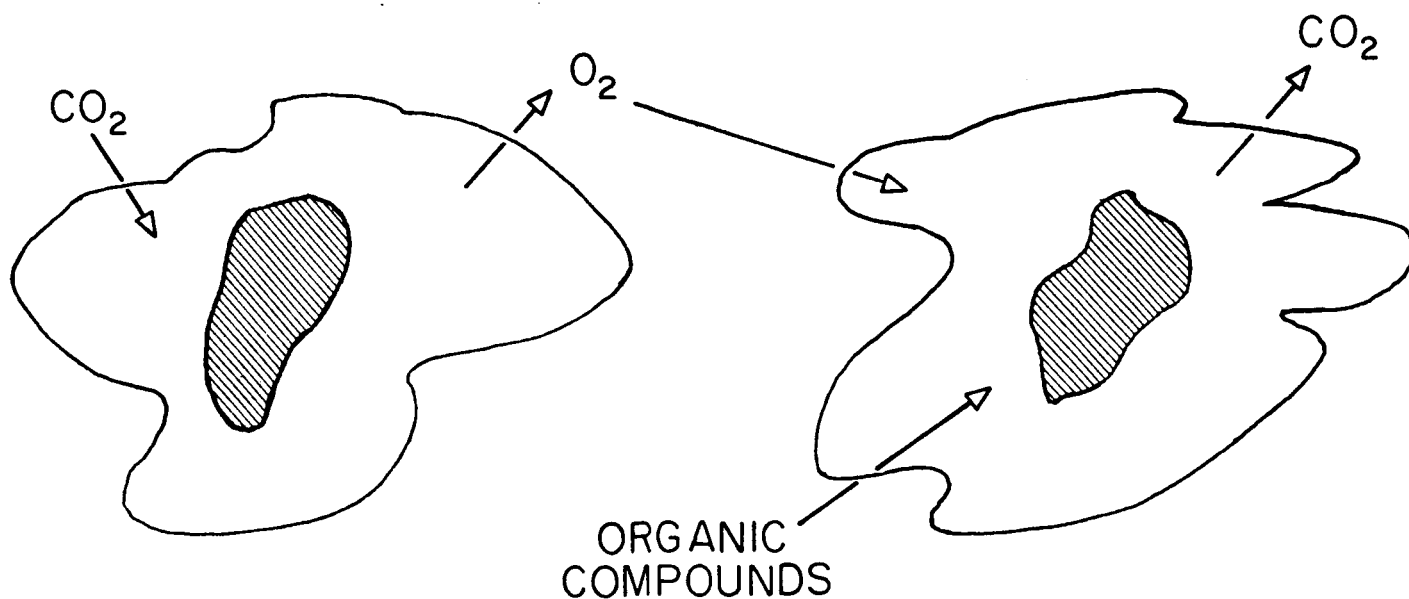


FIGURE 2. SIMPLE FERMENTATION IN COACERVATES OR MICROSPHERES UNTIL THE DEVELOPMENT OF NUCLEIC ACIDS LEADS TO INTERNAL CONTROL OF CELL FUNCTIONS AND FORMATION OF TRUE CELLS CAPABLE OF PHOTOSYNTHESIS AND RESPIRATION :



(ADAPTED FROM YOUNG AND PONNAMPERUMA, 1964)

atmospheric electrical charges. These molecules would be quite soluble in the droplets of liquids present, creating the conditions necessary for complex organic reactions. A possible pathway toward the beginnings of life, given these initial conditions, has been outlined by Wilson (1960) for the analogous stage in the history of the Earth's biogenesis. Wilson has suggested that large quantities of high-molecular-weight hydrocarbons with surface polar groups could have been synthesized in a reducing atmosphere during electrical disturbances, perhaps on clouds and rain droplets caught in the corona discharge of thunderstorms. Of the very large number of polar groups present, some of them might have been of the right kind and the right geometrical orientation to endow hydrocarbons with "enzymatic" activity. Thus, early steps in the chemical evolution of life may have been based on catalysts or "proto-enzymes" in which the catalytic groupings were supported on material of the hydrocarbon type. This "hydrocarbon life" could then have evolved until it was sufficiently developed to be able to synthesize its own macromolecules (cp. Fig. 2).

3.2 Laboratory Studies of Simulated Jovian Atmospheres

Support for the concept that organic compounds regarded as possible precursors of life systems may have developed in the reducing atmosphere of Jupiter comes from laboratory studies with simulated Jovian atmospheres. Atmospheres comprised of methane, ammonia, hydrogen, and water vapor have been exposed to ultraviolet light, electric discharges, ionizing radiation,

and heat with resultant formation of significant amounts of organic compounds, e.g.:

- (a) Ethane
- (b) Ethylene
- (c) Acetylene
- (d) Adenine
- (e) Hydrogen cyanide
- (f) Amino acids
- (g) Sugars

Confirmation of the production of such organic compounds has been reported by a number of independent investigators. Sagan and Miller (1960) found that electric corona discharges passed through a mixture of 30 parts H_2 , three parts CH_4 , and one part NH_3 , which is roughly equivalent to the composition of Jupiter's atmosphere (although very underabundant in H_2) produced ethane, ethylene, acetylene, cyanide, and acetonitrile; formaldehyde was produced if water vapor was present. In an earlier study, Miller (1957) produced a continuous 60,000 v spark in a sealed vessel containing CH_4 , NH_3 , H_2O , and H_2 and after a week found a variety of amino, hydroxy, and aliphatic acids in the reaction mixture. The first reaction products appeared to be hydrocyanic acid and aldehydes with subsequent synthesis of amino acids directly related to the formation and utilization of these compounds.

Oro and Kimball (1961) synthesized adenine in substantial amounts by heating a solution of HCN in aqueous NH_3 for several days at moderate temperatures (27-100°C). Since adenine

is an essential building block of the nucleic acids (DNA and RNA) and of important coenzymes (e.g., ATP, essential for production of energy in living cells) and since NH_3 and H_2O are common natural constituents of the solar system, while HCN is easily produced from existing constituents (Abelson 1966), these experiments were considered to be significant in relation to the origin of life.

Ponnamperuma (1965) demonstrated that when an aqueous solution of HCN is exposed to ultraviolet, the resulting products included adenine, guanine* and urea. Moreover, the reaction with HCN can proceed even without a source of energy; an aqueous solution of HCN left standing at -10°C is converted spontaneously into a more complex organic compound. There is considerable interest in HCN since it is a pathway for the production of purines** and together with formaldehyde undergoes the Strecker synthesis to give rise to amino acids. Lowe, Rees, and Markham (1963) note that synthesis of amino acids under primitive atmospheric conditions appears to be successful so long as the medium is reducing, but under oxidizing conditions the products are negligible. The significance of the possible formation of amino acids is that they may conceivably be simultaneously condensed to polymers which have many of the properties of proteins, one of these properties being the tendency to form structured units. Prepared in the laboratory these units appear to have many of the attributes of living cells.

*Another base (like adenine) found to occur in nucleic acids.

**Both adenine and guanine are purines.

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3.3 Significant Characteristics of Terrestrial Micro-Organisms

The relative morphological simplicity and unusual environmental interrelationships of certain bacterial organisms have suggested the possibility that such organisms may have existed in a primitive environment very different from the conditions now found on the Earth. Although the chance of finding truly primitive organisms seems remote, remnants of biochemical systems which did exist in the primitive organisms might be identified. For example, such a system might be present in the anaerobic methane bacteria which are able to take up hydrogen and release methane (Wood 1961). Studies of species having these characteristics are relevant to our present problem in two ways. A demonstration that organisms we now observe required a reducing environment for their origin strongly supports the idea that biogenesis could occur in the present environment of Jupiter. In addition, the fact that we still find such organisms on the Earth although average conditions have drastically changed since the origin of these species emphasizes the importance of micro-environments and the extraordinary range of conditions in which life as we know it can exist.

As an example of this second point, the ability of some organisms to withstand very low temperatures can be cited. Becquerel (1950) demonstrated that bacterial spores can survive temperatures less than 1°K. Meyer, et al. (1962) collected samples of water from Don Juan Pond in the Antarctic and found

microflora to exist at temperatures down to 250°K and possibly lower. There appeared to be a direct relationship between the salt concentration of the water and the ability of micro-organisms to survive at low temperatures in a self-sustaining environment. In the atmosphere of Jupiter, mixtures of ammonia and water conceivably could serve as natural antifreezes to permit survival of micro-organisms at temperatures well below 273°K.

3.4 Liquid Ammonia as a Substrate for Life Forms

One aspect of the exobiology of Jupiter which has received comparatively minimal attention, but which cannot be discounted with certainty, is the possibility that liquid ammonia may act in a manner analogous to water as a substrate for life forms. An obvious disadvantage of ammonia, however, is the fact that it remains liquid over a much narrower temperature range than water. At one atmosphere pressure, the boiling point of ammonia is -33.3°C and the freezing point is -77.7°C. To keep ammonia in the liquid state, the temperature must not rise above approximately -40°C. However, at the higher pressures encountered below the cloud layer ammonia may remain a liquid at elevated temperatures. Sagan (1961) notes that liquid ammonia is an excellent organic solvent and on low temperature planets such as Jupiter, where it might be available in abundance, systems of organic chemistry may develop with the NH_2 group replacing the OH group.

Firsoff (1966) has postulated that seas of ammonia and atmospheres of nitrogen might be able to support life on other planets. Processes of digestion which rely on hydrolysis would be replaced by ammonolysis. Reactions of chemical degradation which yield energy by oxidation in our system would take place in an ammonia system through the agency of nitrogen. Instead of water and carbon dioxide as final products, there would be ammonia and cyanogen, the latter being the ammono analogue of carbon dioxide. Despite these arguments, the apparent majority opinion amongst investigators at present is that a water based organo-chemistry is more likely than one based on liquid ammonia.

3.5 Summary

Theoretical considerations supported by the limited experimental data presently available constitute a basis for postulating that precursors of life forms, and possibly some form of life itself, may exist in the environment of Jupiter. Obviously, further theoretical and experimental investigations are required to obtain definitive information that will either support or negate a Jovian exobiology. More specifically, the various strata of Jupiter's atmosphere will need to be examined with regard to:

- (a) Composition
- (b) Temperature range
- (c) Density
- (d) Presence of water
- (e) Levels of solar and other forms of energy
- (f) Presence of particulates (organic compounds, micro-organisms).

At present it seems likely that simple organic molecules may be formed in the primitive reducing atmosphere of Jupiter, probably evolving from exposure of methane and ammonia to solar radiation or electrical disturbances. Over some period of time (depending on local concentrations and temperatures) the simple molecules could have combined to produce complex molecules and subsequently polymers. Concentration and organization of these polymers with the development of an integral form surrounded by a selectively permeable membrane could result in living single cell entities.

This review has taken a deliberately optimistic stance since tradition has been hard on the outer planets with respect to their biological importance. To provide a proper perspective, two points implicit in the discussion given above should be re-emphasized. First, it is by no means completely certain that terrestrial life originated in an environment identical with that presently found on Jupiter. The alternative pathway suggested by Abelson (1966) has already been referenced. Second, even if life on our planet did originate under "Jovian" conditions, we cannot be sure that it would originate in such conditions as they exist on Jupiter. The apparent static quality of this reducing environment which may have maintained roughly the same characteristics we observe today for 4.5 billion years may only be conducive to some kind of primitive, steady state, abiogenic organic chemistry. The main point to emphasize is that even this would be interesting. One of the

most striking aspects about life is its intrinsic improbability as a natural phenomenon. This necessitates a huge number of trials before a successful "origin" can be expected, making the laboratory duplication of the process very difficult, even when the environment can be controlled in such a way that the probability can be greatly increased. In this sense, Jupiter represents a huge natural laboratory in which pre-life experiments may be taking place continuously. The question to be answered is how far these experiments have progressed, that is, to what level of complexity?

If oxygen concentrations sufficient to permit respiration became available there would be a corresponding demand for complex biological functions leading to multi-celled organisms. In fact, nearly a century ago, Louis Pasteur reported that primitive organisms capable of living either with or without oxygen shift from fermentation (without oxygen) to respiration (with oxygen) whenever the amount of available oxygen reaches one-hundredth of the present-day level of oxygen in the Earth's atmosphere. Respiration then provides the opportunity for the development of complex multi-celled organisms. Since Jupiter obviously still possesses a reducing atmosphere, it is extremely unlikely that evolution has proceeded this far. However, if primitive organisms could be identified and isolated in an environment of this type, the way would be open for an experimental approach to evolutionary biology that could critically test Pasteur's observation.

4. THE BIOLOGICAL EXPLORATION OF JUPITER

In the preceding sections, it has been demonstrated that Jupiter indeed appears to provide an appropriate environment for biological investigations. It is now pertinent to consider how such investigations may best be carried out. Since space missions to Jupiter are still several years in the future, it is reasonable to begin with a discussion of what measurements of biological interest are possible from ground-based, sub-orbital, and orbital observing stations. The results obtained from such studies are expected at least to produce valuable background material for the space missions that are next considered. These missions fall naturally into two categories, the first consisting of flybys and orbiters and the second of atmosphere-entering probes. Landers form a possible subdivision of the second category.

It should be emphasized at the outset that missions involving the deployment of atmospheric probes are by far the most significant from a biological point of view. If the reasons for this are not already apparent, they should become clear from the following discussion of the kinds of information that are obtainable from each method of investigation.

4.1 Near-Earth Observations

All of the data described in Section 2 have been obtained from ground- or rocket-based observations, and it is these data which have formed the basis for a biological interest in Jupiter. Hence such observations are obviously germane to

a biological investigation; the question is, can we expect any additional results of importance from these techniques? An affirmative answer is easily supported. It has been demonstrated in Section 3 that present ideas about the origin and development of life on Earth suggest that the presence of liquid water and rather moderate temperatures are required, while the pre-biological chemical evolution necessary for the ultimate development of organisms involves the formation of complex organic molecules. What evidence we have indicating the presence of these conditions on Jupiter can be greatly increased by additional observations of the type already employed.

The temperature gradient of the atmosphere below the clouds can be further explored by radio telescopes which are now able to separate the thermal and non-thermal radiation coming from the planet. By obtaining measurements at several wavelengths, it should be possible to probe the atmosphere to different depths. Knowing the gross atmospheric composition and the planet's heat budget, one can then construct a model, consistent with all the observations, giving temperature and pressure as a function of altitude. Infrared temperature measurements will permit a fitting of this model with the upper regions of the Jovian atmosphere, in and above the clouds.

Our knowledge of the composition of the atmosphere can also be considerably improved. A careful search for water vapor in the near infrared (where penetration to regions of sufficiently high temperature appears to occur) should lead either to

detection or a sensitive upper limit. Such a search can easily be carried out with existing or planned equipment during the next few years. The preliminary indications of the presence of organic molecules mentioned in Section 2 can be critically tested by observations at higher resolution in both the UV and the IR. In the former case, an improvement in rocket spectroscopy can be expected, but the best measurements will result from the use of Earth-orbital spacecraft such as the OAO. The infrared region of Jupiter's spectrum (beyond 1μ) is badly obscured by heavy absorptions due to ammonia and methane, but the high resolution spectra presently being obtained by interferometric techniques will permit the investigation of details such as absorptions due to other constituents of possible biological interest within these intense features. An additional gain would result from the use of a high altitude or balloon- or satellite-based observing station to reduce or eliminate interference caused by terrestrial CO_2 and H_2O absorptions.

As these new results become available, they must be integrated into a developing model for the planet's atmosphere that includes theories for the ionosphere, the exosphere, photochemical reactions, etc. Although apparently remote from our main interest - the possibility of a Jovian biology - it has been amply demonstrated in the case of the Earth that such considerations play a key role in developing a completely consistent theory for the origin and evolution of life as we know

it. An improved atmospheric model will also be of critical importance in the development of plans for space missions to Jupiter.

4.2 Observations from a Flyby and Orbiter

In planning ahead to decide what observations of importance can be made from space probes, it must be borne in mind that many of the basic data that presently seem desirable will have been obtained by the time such missions take place. That assumption will be made here and we shall confine our discussion to those measurements which cannot be performed nearly as well any other way.

The great advantage of a space mission to Jupiter is the resulting proximity of a given experiment to the planet. In practice, this means a high degree of spatial resolution. Because of Jupiter's enormous distance from the Earth, this advantage is particularly notable in the present case. There is thus the possibility of detecting local variations of composition or temperature over the disk of the planet, variations that result from local changes in the opacity of the cloud cover. Such observations could be significant in terms of providing clues for the identification of the most promising regions of the planet for detailed investigation. This would be especially true at radio wavelengths where ground-based resolution is very poor. High resolution television may provide similar insights into the "fine-structure" of the upper Jovian atmosphere and would be especially valuable for interpretation when used with

the other measuring techniques. Finally, a powerful radar with the ability to probe below the cloud layer in search of a surface (solid or liquid) would provide invaluable information concerning the likelihood of biologically favorable environments.

An orbiting spacecraft has considerable advantages over a flyby, not in the types of measurement that can be performed but in the duration and relative location of the measurements. A long observing time and greater areal coverage of the planetary disk can be very useful when investigating the atmosphere of a planet with such rapidly changing cloud configurations. It is quite likely that the effective level of penetration into the atmosphere at any given wavelength will be highly variable, particularly when the planet is observed with high spatial resolution. The increased reliability associated with repeated measurements is also a factor in favor of the orbiter mode.

It must be acknowledged that the information resulting from an orbiter or flyby mission, while useful and interesting, is still very likely to have only an indirect bearing on the key question regarding Jovian biology, viz. is there anything alive on the planet? Nevertheless, the secondary problem of the suitability of the environment for the generation of life and the implications of these results for theories of terrestrial life-development can definitely be pursued in this way. To answer the primary question we must penetrate the atmosphere.

4.3 Atmospheric Probes and/or Landers

From the discussion given in Sections 2 and 3, it should be clear that the region below the clouds is the most probable location on Jupiter either for life itself or for the most complex and interesting pre-life forms. It is here that temperatures are warm enough to permit the presence of liquid water, and here that complex organic molecules, once formed, will be sheltered from the solar UV radiation that would tend to dissociate them. An atmospheric probe provides possibly the only means of investigating this region of the planet directly and of definitively locating and identifying these biologically interesting entities. Unfortunately, due to the enormous gravitational well and dense atmosphere of Jupiter there is a possibility of completely vaporizing an entry probe while it is still above the clouds.

The problem of getting an instrumented capsule into the Jovian atmosphere has been considered in ASC Report No. S-4 (Gilligan 1967). While difficult, it appears that atmospheric entry will be feasible even with existing technology. Advances in technology that may reasonably be expected by the time such missions are actually attempted should ensure their success. Whether or not there is any point in trying to send a lander depends on the presently unresolved question of whether or not there will be anything on which to land! Even if Jupiter has no clearly defined surface, however, it should be possible for a descending spacecraft to reach an equilibrium position not

unlike that achieved by Archimedes in his bath. We may thus consider both types of spacecraft, the difference between them being largely one of survivability and the resulting amount of time available for observations.

In the case of a non-survivable atmospheric probe, the available time is extremely short. Perhaps the most we can hope for is an in situ determination of general conditions (temperature, composition, etc.) below the cloud layer and some direct evidence about the presence or absence of a stable planetary surface. It would be quite interesting, for example, if such a probe definitely detected water in relatively large quantities, found temperatures in excess of 273°K, and reported an increase in the concentration of organic molecules with increasing temperature, i.e., increasing penetration below the clouds. It is doubtful that more than this can be asked of a rapidly traveling, sparsely instrumented probe en route to destruction. Nevertheless, if it were possible to send in such a probe equipped with a television camera (i.e., something similar to the Ranger spacecraft), some additional direct evidence of life or pre-life forms might be obtained.

It is the survivable lander (or floater) that provides the most interesting possibilities, however. Here we may look toward the attempts currently being made to prepare instrumentation for the biological investigation of Mars. In the case of Jupiter, we would need different types of biological detectors since we will be searching for life in a reducing environment,

probably in an exceedingly primitive state. Nevertheless, the technology for remote detection of living organisms being developed for use in the inner solar system will have application for the study of Jupiter. The important point is that all of this technology presupposes the deployment of a lander. Only in this case is there sufficient time and an adequate freedom from modifications of the immediate environment caused by the probing vehicle to permit a definitive investigation of this environment for the presence of living organisms.

5. CONCLUSIONS

Man's primary expectation of finding extraterrestrial life in the solar system has traditionally been focused on the inner planets, with particular attention paid to Mars. It was felt that the outer planets were so far from the Sun that they would be too cold to support life. In addition, what little was known about their atmospheres suggested that they were composed of substances inimical to the survival of life as we know it.

It has been demonstrated in this report that in the case of Jupiter such pessimism is no longer justified. There are now several lines of evidence that suggest the presence of a temperate region in the planet's atmosphere below the visible cloud deck. There are sound theoretical arguments that are beginning to gain observational support which show that the production of complex organic molecules in the Jovian atmosphere is extremely likely. Finally, from reasoning based on presently

observed cosmic abundances of the elements, it is possible to show that the presence of relatively large amounts of water in the atmospheric strata below the clouds is virtually certain.

These conditions are still obviously very different from those existing on the Earth at the present time. However, if one asks what conditions existed at the time life began on the Earth, the answer is surprisingly similar to a description of the present Jovian environment. It thus seems very likely that one at least has the opportunity to investigate a pre-biological environment that is charged with all the prerequisites necessary for life to begin. It is then but a small step to consider the possibility that this vital transformation has in fact occurred and that primitive micro-organisms of the type that first appeared on the Earth may now be present on Jupiter.

The exploration of this planet thus takes on a new character and should receive additional attention from exobiologists. This developing biological interest in Jupiter should also be reflected in mission planning. The most important missions from this point of view are those resulting in the deployment of survivable atmospheric probes, as these represent the most direct way of exploring that part of the planet's environment that is of greatest interest biologically, the region below the clouds. But before this step is reached, much additional information of value in further defining the biological importance of Jupiter can be obtained from orbiters,

flybys, and from ground-based observations. It is strongly urged that such programs be undertaken.

We are thus faced with a curious reversal in our thinking about the life-supporting capabilities of the planets. As additional information about the atmospheres and surfaces of Mars and Venus becomes available, these planets seem less favorable locations for life than previous discussions of the problem had indicated. It is thus refreshing to find that Jupiter appears to constitute another goal for man's determined quest for an alien biology.

REFERENCES

- Abelson, P. H. 1966, Proc. Nat. Acad. Sci., 55, 1365.
- Becquerel, P. 1950, Comp. Rend., 231, 1392.
- Bernal, J. D. 1951, The Physical Basis of Life (London: Routledge and Keagan, Ltd.).
- Firsoff, V. A. 1966, Discovery, 27, 36.
- Gallet, R. M. 1963, Proc. NASA Conf. on the Planet Jupiter (in preparation - see preliminary report in Physics Today, 16, 19 (1963)).
- Gilligan, J. 1967, Thermophysical Aspects and Feasibility of Jupiter Atmospheric Entry, ASC/IITRI Report No. S-4.
- Greenspan, J. and Owen, T. 1967, (in press).
- Low, F. 1966, (private communication - to be published).
- Lowe, C. U., Rees, M. W. and Markham, R. 1963, Nature, 199, 219.
- Meyer, G. H., Morrow, M. B., Wyss, O., Berg, T. E., and Littlepage, J. L. 1962, Science, 138, 1103.
- Miller, S. L. 1957, Biochem. Biophys. Acta, 23, 480.
- Oro, J., and Kimball, A. P. 1961, Arch. Biochem. Biophys., 94, 217.
- Owen, T. 1965, Astrophys. J., 141, 444.
- Papazian, H. A. 1959, Pub. Astron. Soc. Pac., 71, 237.
- Ponnamperuma, C. 1965, The Origins of Prebiological Systems, (New York: Academic Press).
- Sagan, C. 1961, Rad. Res., 15, 174.
- Sagan, C. and Miller, S. L. 1960, Astron. J., 65, 499.

REFERENCES (Cont'd)

- Sagan, C. E., Lippincott, E. R., Dayhoff, M. O., and Eck, R. V. 1967, Nature, 213, 273.
- Urey, H. C. 1959 in Handbuch d. Phys., ed. S. Flügge, (Berlin: Springer Verlag) 52, 400.
- Wald, G. 1964, Proc. Nat. Acad. Sci., 52, 595.
- Wildt, R. 1939, Mon. Not. R. Astron. Soc., 99, 616.
- Wilson, A. T. 1960, Nature, 188, 1007.
- Witting, J. M., Cann, M. W., and Owen, T. C. 1965, Critical Measurements on Early Missions to Jupiter, ASC/IITRI Report No. P-10.
- Wood, W. A. 1961, The Bacteria, Vol. 2, (New York: Academic Press).
- Young, R. S. and Ponnampetuma, C. 1964, Early Evolution of Life, (Boston: D. C. Heath & Co.).